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PENETRATING POWER OF PARTICLES IN ATMOSPHERIC COSMIC RAY SHOWERS

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Phys Inst imeni P. N. Lebedev
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8 Aug 1947

/Tables and figures are appended./

In autumn 1946, at Pamir, at an altitude of 3,860 meters above sea-level, the penetrating power of particles in atmospheric showers of cosmic rays and the nature of these particles were studied with counters.

Apparatus

All experiments used self-quenching counters filled with 85 percent argon and 15 percent propylene with a total pressure of 100 millimeters of mercury. A gaseous hydrocarbon was employed as the polyatomic admixture instead of alcohol vapor, because of favorable experience gained in using this type of counter during the 1945 expedition, when one of the authors of our article (G. T. Zatsenin) filled the counters with a mixture of argon and ethylene. Those counters containing a gaseous hydrocarbon (but not methane) as the polyatomic admixture possessed excellent characteristics: in particular, they had particially no temperature coefficient and could work during heavy frosts. Ordinary Trost counters break down even at temperatures not far above zero, which makes them unsatisfactory under field conditions. The counters were made of glass 2 millimeters thick. The silver-plated inner surface of the glass acted as a cathode. The effective cross section of each counter equaled 230 square centimeters; the diameter was 6 centimeters.

Coincidences of pulses from various groups of counters were recorded by a multichannel amplifier, by means of which it was possible to measure simultaneously the coincidences of two different multiples up to sixfold coincidences. The resolving time of the amplifier was $\tau = 2.6 \cdot 10^{-6}$ second.

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Extensive Showers

In the first series of experiments, coincidences from three groups of counters, arranged in a horizontal plane in the shape of a triangle covered on all sides with lead, isolated a penetrating shower. Each group consisted of two counters in parallel. The distance between the counter groups was 1.6 meters. The number of coincidences was recorded for various thicknesses of the lead layer over the counters. The data obtained is tabulated in Table 1. As may be seen from the graph in Figure 1 (curve C_3), the number of coincidences decreases approximately exponentially with thickness of the lead, and the absorption coefficient, for lead thicknesses exceeding 12 centimeters, drops somewhat.

Extensive "penetrating" showers have been recorded under 12 centimeters of lead by many authors [1, 2]; it was generally assumed that meson showers were being recorded. Such an assumption hardly conforms with our absorption curve.

To answer conclusively the question of whether the particles of such atmospheric showers are mesons or light-weight shower-producing particles of high energies, we studied the energy losses during the passage of particles through an absorber. For this purpose, we placed still another layer of aluminum, 10.5 centimeters thick, above the 12-centimeter lead layer on top of each counter. During ionization losses, this layer was the equivalent of 4 centimeters of lead; but during radiation losses by light particles it was equivalent to only 6 millimeters of lead. The experiment showed that absorption by aluminum corresponded, within the limits of experimental error, to absorption by 6 millimeters of lead; in other words, these shower particles sustained chiefly radiation losses. Thus at 4 kilometers, during the recording of extensive dense showers that penetrate 12 centimeters of lead (in a system of triple coincidences there is little probability of recording low-density showers), we were not dealing with meson showers, but with showers of an electron-photon character.

It is difficult to reconcile the great number of electron-photon showers recorded under 12 centimeters of lead with the data of the cascade theory. In the first place, the average energy required by an electron to pass through 12 centimeters of lead is of the order of magnitude $2 \cdot 10^{10}$ eV. That part of the particles in a shower having energies higher than those shown is very small and cannot explain the number of showers observed. In the second place, the streams of particles of such energy must be smaller in dimension than the experimental apparatus itself; therefore, the probability that the apparatus will record such showers is greatly limited.

But the cascade theory, which uses maximum values for the absorption coefficient of photons, is applicable only for light elements. In lead, however, photons of energies 10^6 to 10^9 eV have a reduced absorption coefficient.

S. Z. Belen'kiy's method [3] of calculating the dependence of the absorption coefficient of photons upon their energies was used to show that the penetrating power of shower-producing particles in lead was considerably higher than generally assumed. The energy required by an electron to pass through 12 centimeters of lead is reduced to approximately one fifth. This means that the observed absorption factor of showers, up to 12 centimeters of lead, agrees with the cascade theory in the assumption of an effective energy spectrum of shower particles of the form E^{-1}. But the difficulty in regard to the extent of particle streams of such energy is not eliminated.

Thus the results of experiments obviously attest the invalidity of the cascade theory when applied to sizes such as that of an Auger shower. This evidently also confirms the results of another expedition [4] of ours.

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Some observed diminution in the absorption factor in a 16-to 18-centimeter lead field does not easily agree with the assumption of a purely electron-photon composition for a shower. The penetrating particles are evidently an important factor in this region of the absorption curve; the existence of these particles in Auger showers is abundantly confirmed [5 - 8].

It should be noted that Cocconi, Loverdo and Tongiorgi's results [7] in similar studies of Auger showers at 2,200 meters differ somewhat from ours, since according to their data absorption was not observed when measurements were made with lead 16 to 24 centimeters thick. But the difference in the results obtained may be explained by the difference in the altitudes of observation. Since the energy of shower-producing particles diminishes rapidly with an increase in atmospheric depth, the energy spectrum of shower particles becomes sharply weaker. Consequently, if the showers in the presence of lead thicknesses corresponding to the diminishing section of the absorption curve are thought of as recording high-energy electrons and photons, then this section should become much steeper with decreasing altitude and, at an altitude of 2,200 meters, the electron-photon part of the shower under 16 centimeters of lead should practically not register at all, whereas at 3,800 meters it may still play a dominant role. The extremely sharp high track of extensive showers confirms this data [9].

To estimate the density of a shower in air when recorded by counters arranged under lead, the percentage correlation of coincidence was measured from three groups of counters screened by lead 12 centimeters thick, with pulses from a fourth group of counters without screens. When the area of unscreened counters equalled the area of counters under lead, the percentage correlation of coincidence was (90 ± 5); when the area was one eighth, the correlation was reduced to only 70 percent. This was confirmation of the great density of the accompanying shower (the average density was about eight times greater than that of a shower isolated by triple coincidences from unscreened counters).

Influence of the Effects of Particle Scattering Upon Observations

Interesting data on the influence of scattering upon the recording of showers was obtained. Triple coincidences were recorded.

An over-layer of lead was placed on each of three groups with a single counter, as shown in Figure 2a. The number of coincidences was measured for two cases: (1) the counters were screened with lead on the top and sides, but not at the bottom; and (2) the counters were screened with lead on all sides. It was found that in the second case the number of coincidences observed was 30 percent less than in the first case. Similar results were obtained when lead was placed over each group with two counters (Figure 2b). The increase in coincidences with lead underneath in this case proved, as was to be expected, to be less appreciable; to be exact, about 15 percent. The results of these experiments are evidently the consequence of reverse scattering in the lower lead interlining and of particles escaping the counters in their track from top to bottom. Thus, placing lead underneath produces an increase in the effective area of the counters, and this effect is dependent upon the configuration of the screening (Figure 2, a and b). Such great influence from reverse scattering is in good agreement with the conclusion that a huge majority of the showers recorded by our apparatus are made up of electron-photon showers.

However, it was found necessary to screen counters underneath. Without underneath screening, certain showers were recorded, in which the particles did not pass through the lead layer, but hit the counter, escaping the lead and scattering in the ground (Figure 3). This effect of pseudo-recording of "penetrating" showers is observable with great thicknesses of lead, when the real effect from showers penetrating the lead is actually small. A corresponding experiment was made with a lead layer 20 centimeters thick placed over the counters. In this case, when the counters were not screened underneath, the number of recorded showers equaled 0.84 ± 0.15 per hour, but in screening with 6 centimeters of lead the number registered dropped to 0.44 ± 0.15 per hour.

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Study of Low-Density Showers

The following measurements were made by an apparatus in which the passage of all but two C_2 particles could be recorded. Apparatus of this type records low-density showers with a greater degree of probability than a system of triple coincidences. If the particles entering into the composition of low-density showers are assumed to be of another nature, then the absorption curve obtained by such apparatus should differ from the absorption curve described above.

Since in recording double coincidences a considerable number of them are incidental, we measured the number of coincidences between two "wide-angle" telescopes (Figure 4). With reference to recording showers, such a system is to some degree merely the equivalent of two counters. The results of measurements on the absorption of shower particles in lead, made by the apparatus represented in Figure 4, are given in Table 2 and in Figure 1 (curve C_2). The data presented is corrected for a number of chance coincidences, amounting to 0.3 per hour for great thicknesses of the lead.

For lead up to 12 centimeters thick, the slope of curves C_2 and C_3 are found to be uniform. Accidentally, even the absolute values C_2 and C_3 almost coincide. But starting from 12 centimeters, the slope of curve C_2 suddenly diminishes and corresponds to a very small absorption factor up to 30 centimeters of lead (Figure 1, curve C_2). Placing a 2-centimeter-thick lead filter between the counters in both telescopes with a 20- and 30-centimeter-thick upper layer of lead did not give any considerable additional absorption beyond the limits of experimental error (25 percent). All this testifies to the fact that the apparatus recorded penetrating particles of atmospheric showers when the layer of lead was very thick.

The ratio C_2/C_3 depends on the density distribution of the streams of shower particles recorded by the apparatus. This ratio increases for sharper drops in the number of showers in the function of density. The increase in the ratio C_2/C_3, for great thicknesses of lead, when the penetrating particles are recorded by the C_2 apparatus, tells us that the density distribution of meson streams in showers differs from the density distribution of electrons.

An experiment was also carried out on the coincidence correlation of telescopes covered with 20 centimeters of lead with three groups of counters not covered with lead, with an effective area four times greater than the counters in the telescopes and 3.5 meters distant from them. Correlations were observed in 40 percent of the cases, which indicates that mesons generally form a part of low-density showers.

The experiments described do not clearly settle the problem of purely meson extensive showers. If the recorded showers composed of mesons form a part of Auger showers, they should have a more extensive spatial distribution than electrons.

The absorption curves C_2 and C_3 may, however, differ because of other causes. A distance of 1.6 meters between telescopes cannot, a priori, be considered sufficient to fully exclude the influence of narrow showers, which are not recorded by a C_3 apparatus in view of their low-density: also, they do not show any correlation with large-area counters that are a considerable distance away (3.5 meters). If only a part of the showers showing a correlation with counters at a distance of 3.5 meters is assumed to be related to extensive showers, then the point of the curve C_2 for lead 20 centimeters thick will coincide with the corresponding point of C_3. In such an event the arguments brought forward in regard to the spatial distribution of mesons would be invalid, as the difference between the curves C_3 and C_2 would be the result of the interference of narrow showers.

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Effects of Distance on Various Apparatus

Work with this apparatus revealed in greater detail the influence of the pseudo-recording of "penetrating" showers in the absence of lead screening under the counters. The number of coincidences between counters 1 and 3, and also between 2 and 4 (Figure 4) with a 20-centimeter lead layer on top, were measured for two cases: (1) when the system was not screened underneath, and (2) when the system was screened underneath with 6 centimeters of lead. The upper counters (1 and 3) registered more coincidences (4.3 ± 1.7) per hour without the lead layer underneath than with. The lower part of counters 2 and 4 when placed on the ground recorded even more such pseudo-"penetrating" showers, namely, 7.2 ± 2.5 per hour (with the number of true coincidences produced by penetrating showers equal to about two to three per hour).

In recording fourfold coincidences (1, 2 - 3, 4), namely, coincidences between telescopes, this effect proved to be considerably less, i.e., the number of recorded showers for no lead underneath was increased by only 0.32 ± 0.30 per hour (the number of recorded true penetrating showers being about one per hour.

These experiments indicate that scattering from the ground, with no screening underneath, becomes larger the less the number of multiples of coincidences from counters screened with lead. The number of such parasitic readings in coincidence recordings from three separately lead-screened groups of counters amounted in our experiments to about 0.4 percent of the showers recorded without lead: during double coincidences it is about 2.5 percent. With screening for only one counter, this parasitic effect should be a large factor.

Narrow Showers

The penetrating power of narrow showers was studied with the apparatus shown in Figure 5. The distance between the axes of the telescopes was 36 centimeters. In making these measurements the counter system was not screened underneath. In accordance with the experiments described above, when the distance between the telescopes was 1.6 meters, this brought about an increase of 0.32 ± 0.30 per hour in the number of coincidences. Assuming that the magnitude of this effect remains as before, with a given counter configuration we can introduce this magnitude into the given measurements to correct them. The results corrected for the number of cases of coincidences and the number of showers scattered from the ground are given in the first line of Table 3. If the number of coincidences produced by particles of extensive showers is assumed not to vary with change in distance from 1.6 to 0.36 meter, then the numbers corresponding only to narrow showers can be obtained by subtracting the corresponding data of Table 2 from the data in the first line of Table 3. The differences obtained are given in the second line of Table 3 and the absorption curve of particles of narrow showers corresponding to them are given in Figure 1 (curve C_2 narrow). In the distance from 0 to 4 centimeters the curve is represented by dots, since there is obviously a transitional effect in this interval.

The absorption curve attests the presence of two forms of particles composing narrow showers. A considerable part of the coincidences observed in an unscreened system is produced by soft particles almost fully absorbed in up to 12 centimeters of lead, and the course of the absorption curves, up to 8 centimeters of lead, is similar for narrow and extensive showers. It is difficult to explain such a form of an absorption curve by the assumption that soft particles are low-energy mesons.

In the interval between 12 and 30 centimeters of lead the number of coincidences within the limits of statistical error does not vary. This fact indicates the extremely penetrating character of the particles responsible for these coincidences. Despite the absence of effective absorptive absorption during great variations in the lead thickness over the telescopes, placing a lead lining 2 centimeters thick between the upper and lower counters of both telescopes reduces the number of coincidences by 30 percent (Table 3). Hence, it follows that under great thicknesses of lead the records made in every case are not only of the primary extensively penetrating particles, but also of the secondary particles already produced in the lead.

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Simultaneously with the measurement of coincidences between the telescopes, recordings were made of the coincidences between pairs of counters 1 and 3. At a distance of 1.6 meters between telescopes, the ratio between the number of coincidences at counters 1 - 3 and 1, 2 - 3, 4 was maintained almost unchanged during a variation in lead thickness and was equal to 2.5. For narrow showers, however, the indicated ratio was also close to the same magnitude when there was no lead over the counters and when the layer was 4 centimeters thick. But starting from 8 centimeters of lead, it increased sharply. A possible factor here may be the isolated mesons of the hard component, moving at a small angle to the horizontal. However, our calculation of the number of horizontal mesons showed that the increase in the ratio $C_2(1 - 3)/C_4(1, 2 - 3, 4)$ cannot be explained by the registration of isolated horizontal particles. We prepared this calculation on the basis of our 1945 measurements at the same altitude. A horizontal telescope composed of three counters 7 x 40 square centimeters in size had two lead linings 7 centimeters thick and was covered on top by 8 centimeters of lead. The distance between the axes of the outer counters was 32 centimeters. Moreover, the number of triple coincidences unaccompanied by a shower in the air was 28 per hour. If this whole number is related to the figure for horizontal mesons and is subtracted, in the same manner as the chance (nine per hour) coincidences, from the total number of coincidences (1 - 3), then the ratio of double to fourfold coincidences will remain double that obtained without a lead layer.

If primary shower particles coming from the air are assumed to be directly recorded under a lead layer, then in order to explain this effect it is necessary to assume that with greater lead thicknesses narrow showers are recorded with a different (more diffuse) angular distribution than the narrow showers recorded without lead, which is extremely unlikely. It is more natural to assume, in accordance with the effect of powerful absorption in the lining, that the secondary and not the primary particles are generally recorded under lead. Then the great difference between the number of coincidences 1 - 3 and 1, 2 - 3, 4 can be explained by the large angles of deviation of the secondary particles produced in the lead.

Since a considerable part of the coincidences under great lead thicknesses are obviously caused by secondary particles, it is difficult to assert that all coincidences observed are caused by particles of narrow atmospheric showers. According to Daudin's data [10], an essential factor in the effect observed can be assumed to be played by very penetrating isolated particles exploding in lead by means of secondary particles, which are already of lesser penetrating power and which fall simultaneously on the counters of both telescopes. Such a mechanism would automatically explain both the sharp difference in the number of double and fourfold coincidences and the effect of absorption in the linings.

However, the total results obtained on narrow penetrating showers obviously indicate that part of the effect observed under lead, especially by the two-telescope methods of observation, is caused by completely true atmospheric showers and is not wholly linked with explosion processes generated by isolated particles in the lead. Furthermore, penetrating particles produced in the lead by the generation of secondary particles must form part of narrow showers.

The formation of secondary particles observed under lead, registering as narrow showers, would explain one interesting effect described in an article by A. I. Alikhanyan, T. L. Asatiani, and G. Muskhelishvili [11]. These authors isolated the penetrating showers by a system of two counters placed separately under 12 centimeters of lead and 25 centimeters apart. By the aid of small counters connected with neon tubes, it was shown that in recording a shower under lead a very great number of particles were observed.

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It follows from our experiments that, with such a distribution of counters, a basic role is played by narrow showers (about 90 percent). A great number of tubes flashing simultaneously indicates that secondary particles are formed in considerable numbers, but not by any means amounting to the very great density (1,000 particles per square meter) of an extensive penetrating shower. The absence of an appreciable number of extensive high-density showers composed of penetrating particles follows quite definitely from the experiments already described.

It is difficult to draw from our experiments any definite conclusion about the nature of the soft particles of narrow atmospheric showers, which obviously constitute the basic mass of particles of such showers. However, it seems to us that it is very difficult to make the form of the absorption curve up to 8 centimeters of lead agree with the meson hypothesis of narrow atmospheric showers. In that case, the mesons constituting the narrow showers would have to have a very strange form of energy spectrum. On the one hand, there should not be any mesons with a range less than 4 centimeters of lead; on the other, almost all mesons should be absorbed by an 8 centimeter lead layer. Thus, their energy should be contained within a narrow interval lying close to 10^8 eV, i.e. close to their rest energy (mc^2), and hence the angular distribution of their departure during generation should be directed only to a slight extent.

Since the showers are recorded as narrow, this means that the generation process originates close to the apparatus. It is extremely difficult to make the latter fact agree with a possible effective cross section of generation and with the possible stream of a generating component. Therefore, the meson hypothesis for narrow showers /12/, in regard to the soft component, is in our opinion extremely improbable. Further experiments are necessary to ascertain the nature of these particles. Observations made with great thicknesses of lead likewise do not reveal the mechanism of the observed generation and the character of secondary particles. The generation of showers in lead, studied by Veksler, Kurnosova, and Lyubimov /13/, and the formation of secondary particles noted by us can be assumed to have a similar character.

Conclusions

1. The extensive dense atmospheric showers which are observed in considerable numbers and which penetrate 12 centimeters of lead at an altitude of the order of 3 to 4 kilometers above sea level are the high-energy electron-photon component of Auger showers and are not meson showers. Further research is necessary to explain the nature of particles of extensive showers observed under greater thicknesses of lead.

2. Two different types of particles form part of the narrow showers, namely:

a. Soft particles that are almost completely absorbed in lead about 10 centimeters thick, which obviously cannot be identified with mesons and which constitute the basic mass of particles of narrow showers.

b. Penetrating particles whose character is difficult to establish, since the apparatus generally used to record narrow showers records for the most part not the primary particles of narrow atmospheric showers, but the secondary particles already developed in the lead.

The authors express their thanks to Academician D. V. Skobel'tsyn and Professor V. I. Veksler for their valuable advice in work and discussions, to Doctor S. Z. Belen'kiy for numerous consultations, and to V. A. Khvoles for developing the multi-channel amplifier system of high resolving power with efficient tubes.

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Table 1

Thickness of lead (in cm)	0	4*	8*	12	16*	20	12 cm lead plus 10.5 cm aluminum
Coincidences per hr	92±2	71±3.5	23.5±0.3	3.5±0.3	1.17±0.2	0.44±0.15	2.54±0.2

NOTE: Data in the case of lead thicknesses marked with an asterisk was obtained without screening the counters underneath the lead. Data revised on the basis of controlled experiments is set forth in the table.

Table 2

Thickness of lead (in cm)	0	4	8	12	16	20	30
Coincidences per hr	116±10.5	65±3.5	13.9±1.3	3.0±0.3	1.65±0.3	1.17±0.25	0.85±0.3

Table 3

Thickness of lead (in cm)	0	4	8	12	16	20	30	20 cm plus 2 cm lining
Coincidences per hr	175±11	118±8	27.4±2.8	15.4±1.4	12.4±1.2	13.4±1.3	12.2±1.4	9.26±0.88
Coincidences per hr	59±15	53±9	13.3±3.0	11.5±1.5	10.8±1.4	12.2±1.5	11.4±1.3	8.1±1.0

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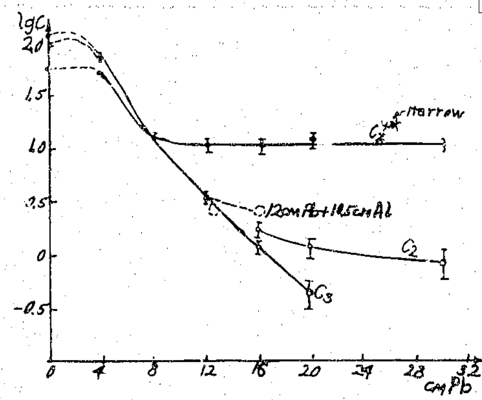

Figure 1

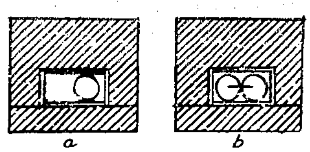

Figure 2

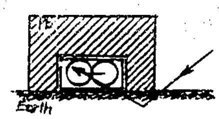

Figure 3

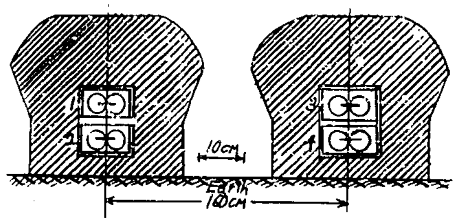

Figure 4

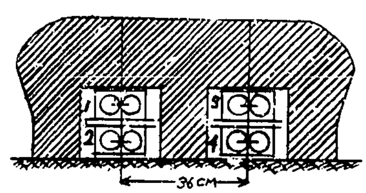

Figure 5

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